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SOLID PROPELLANT COOL GAS GENERATOR

by

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JAMES F. KOWALICK

June 1965

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SOLID PROPELLANT COOL GAS GENERATOR*

by

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**AMCMS Code 5900.22.01105.01
AF MIPR 5-00072**

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June 1965

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ABSTRACT

Solid propellants have been used as sources of high-pressure gases for comparatively short periods of time for running turbines, starting turbo-machines, atomizing liquids, operating pneumatic power tools and, more recently, inflating life rafts, balloons, and collapsible wing structures. One of the major problems encountered in inflatable devices has been the degradative effect of high-temperature propellant gas on materials, resulting in rupture and/or burning of fabric structures. This problem has been eliminated through the use of a packed-bed chemical heat exchanger, thereby reducing effluent gas temperature to an acceptable level.

A method is described for producing rapid and efficient cooling by this technique, such that the temperature of the cooled gases is essentially independent of both flame temperature and ambient temperature. The method involves passing the high-temperature gas through bulk arrangements of chemicals which decompose endothermically and produce further gases that mix with the propellant gases. The resultant mixture has increased mass and a greatly reduced temperature.

Advances in chemical coolant-heat exchanger technology as related to propellant gas-generating systems are described. In particular, design data for specific propellant-coolant systems are discussed, with emphasis on their use for inflatable devices.

INTRODUCTION

It has long been apparent that gases formed from the combustion of solid propellants would offer a convenient means for inflating aircraft flotation bags, life rafts, collapsible structures and supports, weather balloons and the like. However, the high temperatures of gases so formed result in thermal erosion of hoses, rubber valve materials, and fabric walls, causing eventual rupture and/or combustion of the inflatable device. There have been several approaches to the basic problem of reducing the propellant gas temperature. All such approaches provide a heat sink to accumulate thermal energy from the higher-temperature propellant gases. These approaches differ chiefly by the ease of which heat transfer is accomplished.

Several investigators have passed propellant combustion products through a bed of inert metallic particles. Total heat transferred is limited here, however, to the sensible heat absorbed by the bed.

Sutter, et.al., (1)* used the primary propellant gas in an ejector to entrain a secondary stream of ambient air, such that downstream mixing would provide a relatively lower-temperature gas mixture of increased mass (see sketch, Figure 1). The mass ratio of secondary to primary gas approaches zero, however, for downstream pressures much greater than 6 psig. Furthermore, ejectors open to the ambient environment could not be used where there was danger of water or other liquids being entrained by the primary gas stream.

(2)
In a classic letter patent, Maurice and Tavernier disclosed a method whereby the high-temperature product gases pass through a packed, solid chemical bed. The nature of the chemical is such that it undergoes a chemical reaction, producing still further gases that mix with the combustion gases. The result is a gaseous mixture of increased mass and considerably lower temperature than that of the original propellant combustion gases. Outlet gas temperatures as low as 140°F have been reported, using this method. Figure 2 is a sketch of such a system, as used to determine the feasibility of operating a standard pneumatic grinder. This grinder operated for 80 seconds, remaining cool at a generator pressure of 500 psi.

* Numbers in brackets refer to references at the end of this paper

THE CHEMICAL HEAT EXCHANGE PROCESS

The process by which high temperature propellant gas exchanges thermal energy with solid chemicals is exemplified by Figure 3.

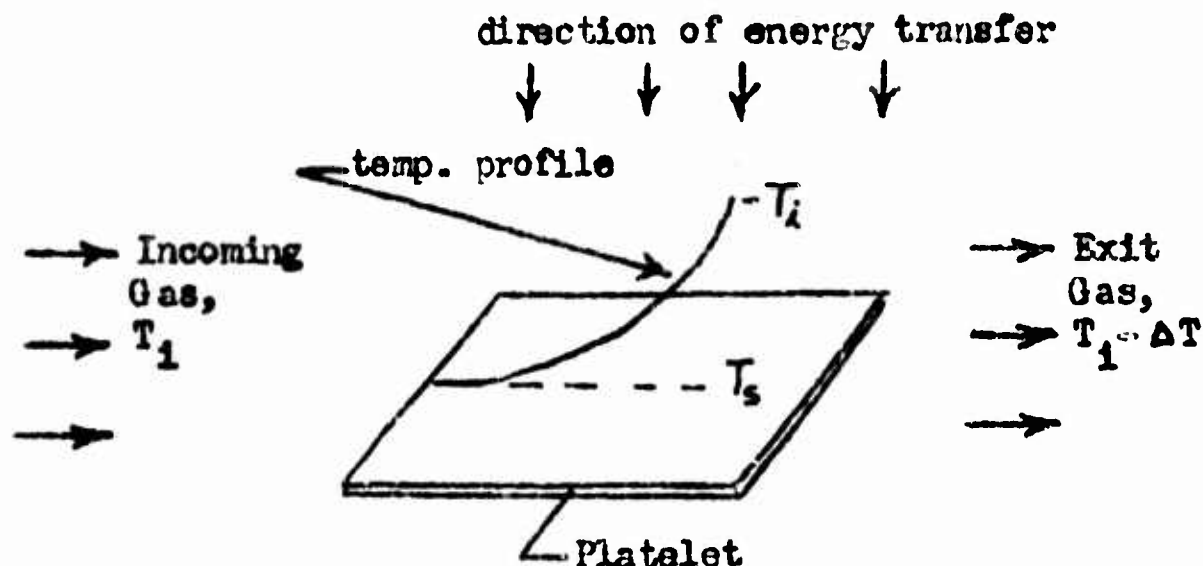


Figure 3. Thermal Boundary Layer along a Coolant Platelet

The sketch here shows a gas stream flowing by a chemical "coolant" crystal having a platelet form, with a flow direction that is one-dimensional. Energy is transferred from the gas to the coolant platelet through a thermal boundary layer, across which a temperature profile has been established. The gas temperature at the surface, T_s , is slightly greater than the decomposition temperature of the coolant, T_d , while the boundary temperature, T_i , is equal to that of the bulk stream. The average gas temperature of the gas mixture leaving the boundary layer is differentially less than the incoming gas bulk temperature. This difference is an indication of the rate of energy being transferred to the platelet. According to Schlichting's solution of this problem, (3) the heat transfer coefficient, h , across a laminar thermal boundary layer for a flat plate (assuming no mass transfer) can be obtained from the relation

$$Nu = 0.664 (Pr)^{1/3} (Re)^{1/2} \quad (1)$$

where Nu = Nusselt Number = hL/k
 Pr = Prandtl Number = $C_p u/k$
 Re = Reynolds Number = $\rho V_{in} L/\mu$

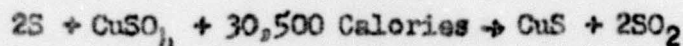
Similar solutions exist for other shapes. Although the assumptions of laminar, steady-state flow and no mass transfer do not strictly apply here, this expression yields an approximate heat transfer coefficient which serves as a starting point in the absence of an exact solution. While the properties of the propellant gas influence the overall heat transfer rate, these are more or less fixed by the choice of propellant. Therefore, it is the orientation, shape, and thermochemistry of the chemical coolant particles that have a controlling influence on the heat transfer process. Qualitatively speaking, the ideal coolant, from the standpoint of obtaining high rates of energy transfer, should have the following characteristics:

1. Low decomposition temperature
2. High thermal conductivity
3. High endothermic heat of reaction
4. High surface-to-volume ratio
5. Long dimension in the flow direction

Such combinations are difficult to find in practice, and it is more often the case that several of these characteristics must be compromised because of stability, toxicity, and compatibility considerations.

CHEMICAL COOLANTS

Representative chemical coolants and their properties are tabulated in Table I. Note that endothermically-reacting mixtures may be considered for coolants, as is illustrated by the anhydrous copper sulfate-sulfur mixture, which decomposes by the reaction*



This reaction results in two moles of gas for every 30 Kilocalories of heat absorbed, or 0.067 moles gas/Kcal.

Table I. Coolant Properties

Ammonium Carbonate	9.15	136°F	16 Kcal
Ammonium Carbamate	13.8	140°F	38 Kcal
Gelatinized Water	2.0	212°F	9.7Kcal
Ammonium Hydrosulfide	14.1	212°F	23 Kcal
Sulfur/Copper Sulfate	3.2	—	30.5Kcal
	Std. Cubic Feet per Lb. Coolant	Transitional Temperature	Molar Transition or Reaction Energy

*Ellem, Modern Pyrotechnics, Chem. Pub. Co., New York, p. 173 (1961)

The general coolant decomposition reaction can be written



One of the most common coolants, ammonium carbonate, $(\text{NH}_4)_2\text{CO}_3 \cdot \text{H}_2\text{O}$, has characteristics approaching those of an ideal coolant. Its decomposition temperature of 130°F is low enough, and heat of decomposition sufficient to be a very efficient heat exchange agent. Furthermore, it is stable at most environmental temperatures under hermetically sealed conditions. Unless water vapor is undesirable as a product for a particular application, industrial grade ammonium carbonate can be used. The industrial grade compound is hydrated and has one molecule of water loosely bound to its platelet structure. Ammonium carbonate decomposes completely to gases upon molar energy absorption of 16 Kcal.

Another compound, ammonium carbamate, $(\text{NH}_4\text{OCONH}_2)$, appears at first glance to have superior coolant properties to ammonium carbonate, since it decomposes completely into non-aqueous gases. However, experimental findings indicate that (1) sublimation is an intermediate process preceding gaseous decomposition, and (2) the sublimed compound, when carried downstream to a lower-temperature environment, reverts to the condensed solid. This process results in an apparent molar gas delivery rate greater in magnitude than the net rate. As applied to an inflatable system, this would require initial over-pressurization for any specified final pressure.

When high-temperature gas exchanges heat with an excess of coolant, the resulting gas temperature approaches the coolant transitional temperature. For example, when ammonium carbonate, $(\text{NH}_4)_2\text{CO}_3 \cdot \text{H}_2\text{O}$, is employed as the coolant, exit gas temperature is approximately 130°F . If there is insufficient gas-to-coolant contact, the resulting gas temperature will be somewhat higher than the coolant transitional temperature, the departure from this temperature being dependent on the degree and duration of contact.

An energy balance is required to determine the minimum quantity of coolant necessary to absorb the available energy from propellant combustion. This quantity is approximated by the ratio Q/λ , where Q is the heat of explosion of the propellant, and λ is either the transitional energy or heat of reaction of the coolant. Under actual conditions, more coolant is required than is determined by this ratio, since the assumptions for minimum quantity are (1) an infinite gas-coolant contact time (or infinite coolant decomposition rate), and (2) negligible

possible heat effect. In practice, the best method for determining this ratio is to conduct a series of tests with variable coolant-to-propellant weight ratios.

MECHANICAL DESIGN OF THE BED

The design of the coolant bed must take into consideration two phenomena which are inherent in packed beds. One of these, "channeling", is characterized by a large fraction of the total flow following the same route through the bed, each increment of flow increasing the cross-sectional area of the channel. Consequently, very little heat is transferred to the solid coolant particles, and the outlet gas temperature is much higher than for the case of intimate gas-coolant contact through the bed. Undesirable effects of channeling in packed beds can be reduced mechanically by (1) dispersing the gas phase through the bed with spray nozzles or with axial perforated tubes, or (2) changing the direction (and increasing flow distance) of the gas by using baffles. Both of these techniques provide increased gas-solid contact area.

The second phenomenon, "blocking", is characterized by solid particles building up a restriction - and ultimately, a complete barrier - to gas flow. Under these conditions, pressure rises as in a closed bomb. Pressure is relieved only if the blockage is broken down or if a safety disk ruptures in the generator. Blocking can be reduced by rounding all flow boundaries and by maximizing the size of outlet ports.

A TYPICAL CHEMICAL COOLANT GAS GENERATOR

Figure 4 is a sketch of a cool gas generator capable of inflating a one-man life raft in less than ten (10) seconds to an ambient pressure of 2 pounds per square inch (gauge).⁽⁴⁾ The ignition train is commenced by a percussion primer which, in turn, ignites a flash igniter mixture adjacent to the propellant. When pressure in the propellant chamber rises to a predetermined value, a disk in the central piston ruptures, permitting propellant gas to flow from the piston, down a perforated spray-tube, and radially outward through the packed chemical coolant bed. The spray tube has washer-type baffles, attached at equi-distant intervals, to change the flow direction and increase flow distance. A multi-perforated "collector" cylinder covers the outlet port. Gas flows out through this cylinder and into the inlet port of the inflatable item. Figure 5 is a pressure-time relationship for an actual inflation. The coolant pressure indicated was measured at the outlet port.

Similar cool gas generators are being tested for use with three-man and twenty-man life rafts, and Rogallo-type inflatable wing structures. All current cool-gas generators are lighter in weight than comparable compressed gas systems. Unlike the compressed gas models, the cool-gas generators cannot be depressurized, since initial interior pressure is ambient. Because of this factor, the need for compressor support equipment is eliminated. Furthermore, flow problems experienced with compressed-gas systems at low temperatures are non-existent, since the range of exit gas temperature in cool-gas generators is narrow.

Future work is oriented toward lighter-weight, cool-gas generators with operation over a broader range of environmental conditions. Three main categories of this effort are coolants, hardware design and materials.

Coolants

Chemical compounds and mixtures are being sought, studied, and classified, using as guidelines the following parameters:

1. Moles of gas formed/Kcal of heat absorbed
2. Stability at elevated temperature
3. Transitional (or reaction) temperature
4. Hygroscopicity
5. Heat of decomposition (or transition)
6. Physical form
7. Molecular weight
8. Compatibility with other parts of the system

Hardware Design

Novel types of baffles and dispersal aids are being tested and studied to determine the physical arrangements which yield an optimum degree of gas-solid contact. In addition, outlet port design is being studied in an attempt to eliminate blockage problems and retain the coolant particles in the coolant chamber.

Materials

Insulation material will be selected to reduce the temperature of the confining metal walls, thus permitting a further hardware weight reduction. Compatibility studies are to be conducted to determine any interaction between coolant, propellant, igniter, and hardware.

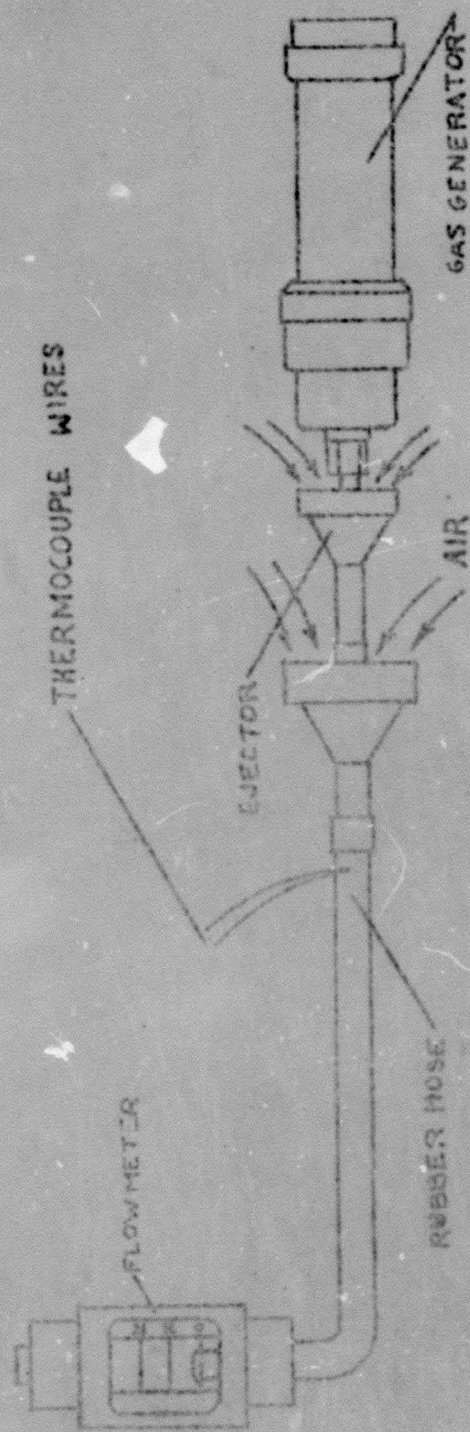


Figure 1. Ejector Test System

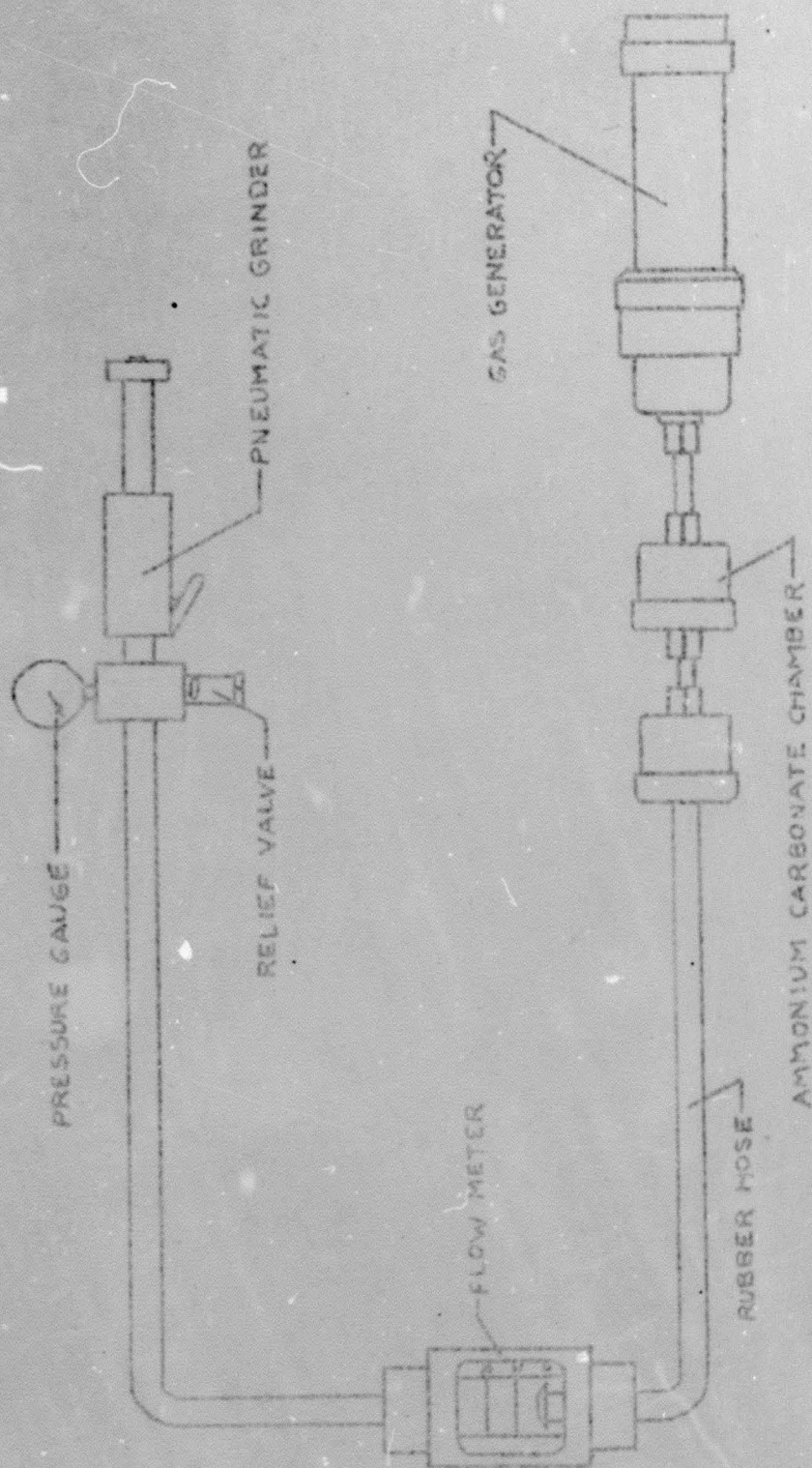


Figure 2. Propellant Gas Generator for Operating Pneumatic Power Tools

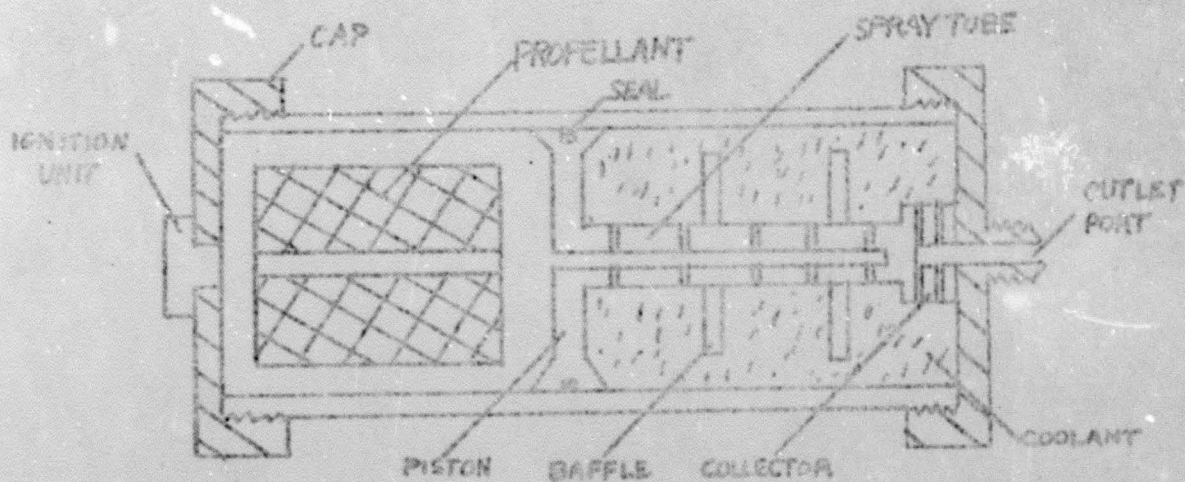


Figure 4. Typical Cool Gas Generator (Longitudinal Cross Section)

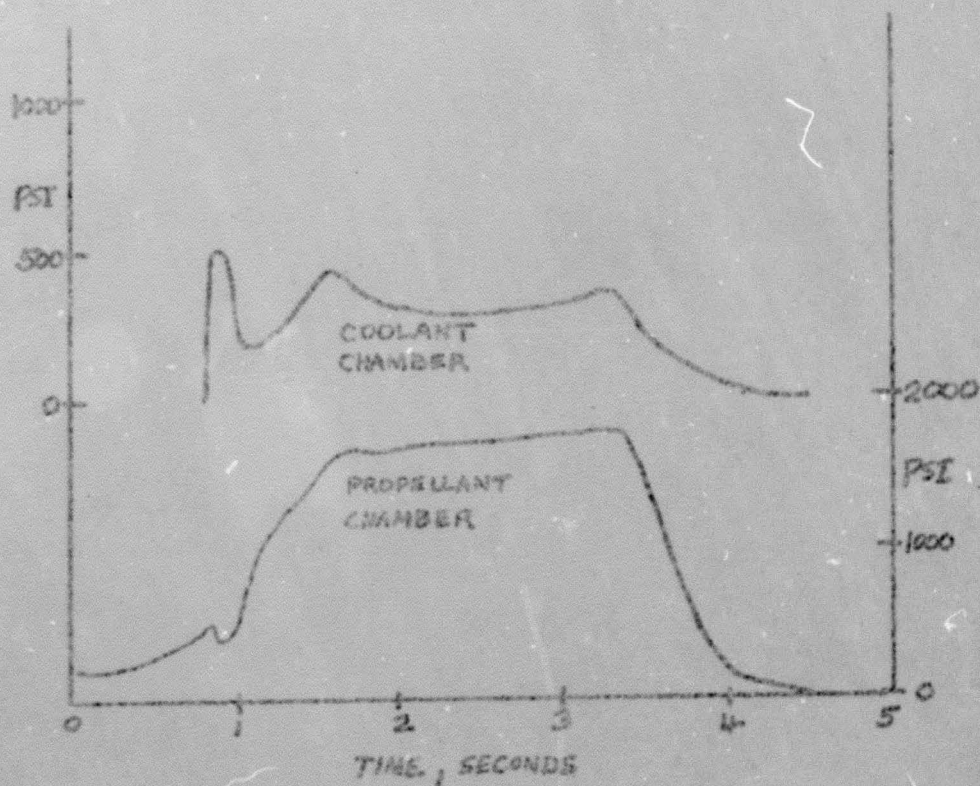


Figure 5. Pressure-Time Behavior of Cool Gas Generator

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